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On plasma formation in CO_2 fusion laser cutting of stainless steel

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Abstract

This paper discusses the mechanisms for emergence of laser-induced plasma (LIP) in fusion CO_2 laser cutting of stainless steel plates. Experimental observations and simulation results are presented to explain why cutting at high velocity increases the risk of LIP formation despite the depleted energy input per unit length.

Keywords: CO_2 laser cutting; real-time monitoring; laser-induced plasma; absorption coefficient

1. Motivation and the state of the art

Laser-induced plasma (LIP) formation is a major concern in CO_2 laser cutting of stainless steel and aluminum. The absorption coefficient of the surface is a function of temperature, the optical properties of the material (determined by composition, temperature, surface roughness) and the properties of the electromagnetic wave (intensity, wavelength, angle of incidence and polarization) [1].

For the CO_2 laser wavelength the absorption coefficient of most metals is substantially less than 1. However, measurements of the laser irradiation reflected from the target surface at different laser intensities indicate that, as soon as the intensity of the incident radiation exceeds the critical threshold value, the absorption coefficient approaches 1. This phenomenon, which is called abnormal absorption, can be explained as a result of formation of laser-induced plasma in front of the target's surface [2]. Plasma starts from vaporization of the molten material where the free electrons in the metallic vapor are accelerated by the inverse Bremsstrahlung process until they gain sufficient kinetic energy to ionize the assist gas or metal vapor to a final density depending on the laser intensity and the loss mechanisms [3]. LIP, when detached from the process front, has a strong lensing effect on the laser beam, i.e. defocuses

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the laser beam and thus considerably reduces the laser intensity supplied to the plate [3]. High-density plasma also acts as a black body, strongly absorbing the laser beam. In this black body condition the subsequently applied laser beam is dispersed and absorbed by the plasma so that the energy of the laser beam is no longer supplied to the workpiece [4]. In this state, further supply of laser beam energy sustains the high-density LIP. Many indications are however available in literature confirming that presence of a limited amount of plasma results in increased thermal coupling between the laser beam and the workpiece [5-7].

High-density LIP is shortly followed by the loss of through cut and consequently irruption of molten material from the top surface of the workpiece, which may damage the nozzle, and the optical components of the cutting head. In order to maximize the productivity and to guarantee production at a high quality level, it is necessary to avoid the strong LIP formation and its shielding effect. Many research efforts have been dedicated to plasma monitoring and control in laser cutting and welding, as described below.

1.1. Plasma monitoring techniques

T. Yamazaki and N. Miyagawa have used the potential difference between the nozzle and the workpiece as a sensing parameter to detect LIP [8]. B. S. Yilbas and Z. Yilbas proved that the absorption of a transverse He-Ne laser beam in the direction normal to the CO_2 laser beam axis is proportional to the intensity of the LIP and thus could be used as an indicator for monitoring [5]. Miyamoto et al. at Osaka University, Japan have determined the time dependent change in temperature of laser-induced plasma by measuring the intensity of two spectral lines of Fe (I) simultaneously (pyrometry) [9]. Miyamoto et al. also used a low-power transverse CO_2 laser beam to determine the spatial distribution of the absorptivity of plasma, based on which the spatial distribution of the plasma absorption coefficient was calculated using the inverse Abel transform. Having calculated the spatial distribution of the absorption coefficient and temperature of the plasma, the spatial distribution of electron density of plasma was calculated based on Eq. 1.

$$N_e = 2.09 \times 10^{14} K_B^{1/2} T^{3/4} \quad (1)$$

where N_e [cm^{-3}] is the electron density, K_B [cm^{-1}] is the absorption coefficient and T [K] is the temperature of the plasma [9].

1.2. Plasma control/suppression techniques

To avoid formation of the assist gas plasma, using helium as the assist gas has proved to be promising due to its high ionisation energy. However helium has the drawback of being more expensive compared to nitrogen. Matile has invented a compromise solution i.e. using a mixture of helium/argon or helium/nitrogen in laser cutting [10]. Burt et. al have invented a method for plasma prevention in laser welding. In this method a side jet of argon is supplied through a tube to blow away the LIP from the interaction zone with the laser [11]. Hidehiko Karasaki has invented a method in which a photo-detector is used to detect the light intensity of the laser-induced plasma. A control unit adjusted the pulse-width of each laser pulse in order to maintain the signal levels between predetermined thresholds [4]. H. K. Tonshoff developed a closed loop control system to avoid LIP formation as follows. A collapsing cutting process has been induced by increasing the feed rate, during which the spectrum of plasma has been recorded by a spectrometer. As soon as a spark is observed in the signal the strong LIP formation is prevented by reducing the feed rate [12]. In order to reduce the shielding effect of the plasma, the electron density must be maintained at a low level. It has been shown that the electron density of the plasma can be affected by applying an external magnetic field [13-16].

LIP formation at high cutting speeds is a well-known fact in fusion laser cutting industry. This, however, seems contradictory since the chance of gas ionization is expected to be directly proportional to the energy input per unit length. The experiments and simulations presented in this article aimed at justifying this contradiction by investigating the underlying mechanisms for LIP formation. The resultant knowledge has been used to develop a closed-loop monitoring and control system for real-time suppression of LIP (not presented in this article).

2. Experimental Setup

The experimental setup shown in Fig. 1 has been used for monitoring of the cutting front during fusion laser cutting[a]. This setup features a high-speed CMOS camera which monitors the cutting front from the side view. Linear cuts were performed in which only half of the laser spot hit the edge of a plate. The camera was placed far enough form the cutting front in a plexi-glass chamber to be protected against the harsh cutting environment. The image acquisition was done via Camera Link protocol using LabVIEW. The tests were performed at laser power of 4 kW with $M^2 = 4.6$ and assist gas pressure of 18 bar. The camera and the cutting head were stationary whilst the plate was moving. Programmatic windowing was done to limit the window of interest only to the cutting front, in order to maximize the achievable frame rate (1000 fps).

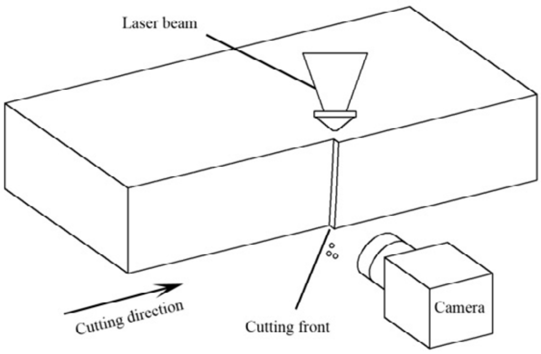


Fig.1. Schematic view of the applied optical monitoring system

3. Experiments and Results

3.1. Origin of plasma formation

A series of qualitative cutting tests was carried out where a plate of mild steel (which is normally cut with flame laser cutting regime[b]) was cut with nitrogen as assist gas and with the same initial cutting

[a] Laser cutting with nitrogen as the assist gas
[b] Laser cutting with oxygen as the assist gas

parameters as would be used for fusion cutting of a stainless steel plate of the same thickness. When the cutting speed was increased, it was observed that LIP emerged in the same fashion as in cutting stainless steel. This observation revealed that the LIP is not primarily associated with the workpiece material but with the assist gas. Given the fact that the first ionization energy of oxygen (1314 kJ mol^{-1}) is lower than that of nitrogen (1402 kJ mol^{-1}), the following factors are most likely to play a key role in ionization of nitrogen (unlike oxygen):

- In fusion laser cutting, once the plasma is formed, it is constantly fed by the high-pressure jet of nitrogen. The assist gas supply is less intense in the case of flame cutting, where the oxygen pressure is typically lower by almost one order of magnitude compared to fusion cutting.
- In flame laser cutting, oxygen forms an exothermic reaction with the molten material. This will reduce the concentration of free O_2 molecules in the vicinity of the process front and thus decreases the chance of ionization. However, this is not the case in fusion laser cutting since nitrogen does not react with the molten steel.

3.2. Effect of energy input on LIP formation

3.2.1. Geometrical effect

Linear cuts were performed on 10-mm-thick AISI 304 stainless steel (Fig. 1) during which the cutting speed was gradually increased in a step-wise fashion. Snapshots of the cutting front at three different speeds are shown in Fig. 2 with dashed lines. A direct relation between the cutting speed and the inclination angle of the cutting front is clearly visible. In other words, at high speeds, the cutting front is effectively longer compared to low speeds. The elongation of the cutting front increases the interaction time between the gas and the molten material and therefore was identified as one of the possible explanations for an increasing probability of LIP formation at higher cutting speeds. Further observations revealed that decrease in energy input (reduced laser beam duty cycle and/or power) and increase in plate thickness also stimulate the LIP formation. This may lead to conclusion that the LIP emerges when loss of through cut is about to happen regardless of the actual cause.

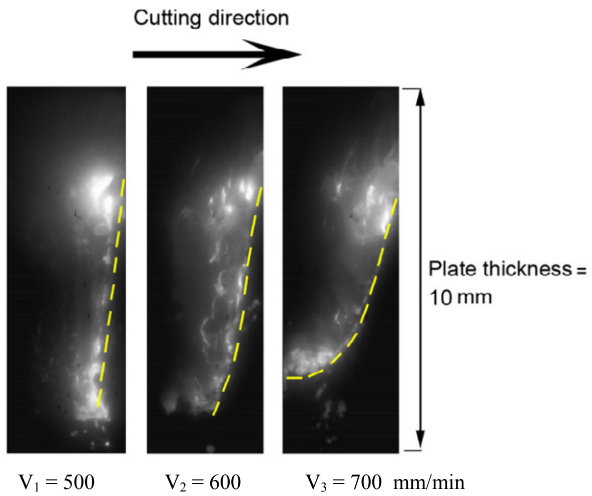


Fig. 2. Side view of the cutting front at three different cutting speeds viewed by a high-speed visual camera

3.2.2. Optical effect

Using the approach presented in [17], the absorption coefficient of the melt layer at the cutting front can be calculated as a function of the incidence angle as shown in Fig. 3. The absorption coefficient is directly proportional to the inclination angle of the process front (see Fig. 3 at incidence angles > 87°). This implies that increased inclination of the cutting front at high speeds results in further absorption of the laser beam and thus increases the melt temperature. This enhances the heat conduction to the assist gas and increases the chance of LIP formation.

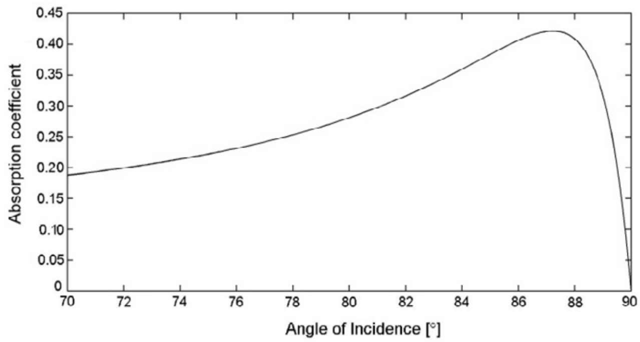
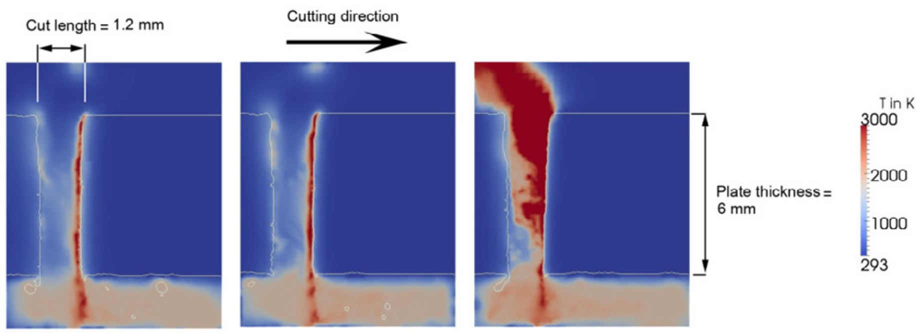


Fig.3. Absorption coefficient of molten iron vs. the angle of incidence for unpolarized CO_2 laser light [17]

Fusion cutting of a 6-mm-thick plate of mild steel[a] has been simulated at three different cutting speeds. A detailed explanation on the model can be found in [18]. Fig. 4 shows the side view of the cut kerf at each cutting speed, with the cutting direction from left to right. Temperature fields and the boundaries of the solid material (white line) are visible.



(a) (b) (c)

Fig. 4. Side view of the cut kerf in simulation of fusion cutting of 6-mm-thick stainless steel (AISI 304) at cutting speeds: (a) 1.26 m/min; (b) 2.10 m/min; (c) 2.94 m/min

[a] Material properties of mild steel were used due to the lack of a complete set of properties of stainless steel AISI 304 at elevated temperatures in the literature.

From a qualitative point of view, these simulation results are in agreement with the above-mentioned experimental observations in several aspects as follows.

- The average temperature of the cutting front seems to be strongly correlated with the cutting speed. The effect is most visible when the temperature fields at Fig 4.a and 4.b are compared. More specifically, in Fig. 4.b, the cutting front is uniformly at the maximum temperature (3000 K), whereas in Fig. 4.a the local temperatures of the cutting front deviate from the maximum by approximately 1000 K.
- At the highest simulated cutting speed (Fig. 4.c), the temperature of the assist gas has been elevated drastically. This enhanced heat transfer can be considered as the cause for the emergence of the LIP at high cutting speeds as observed in the experiments.

  Fig. 5 shows the superposition of three cutting fronts at the same speeds as mentioned in Fig. 4 for the sake of comparison. In Fig. 5, the red, green and blue lines represent the cutting front at minimum, medium and high cutting speed respectively. The inclination of the cutting front seems to be strongly correlated with the cutting speed as was observed in the experiments. The increased inclination, results in increased absorption coefficient of the process front (Fig. 3).

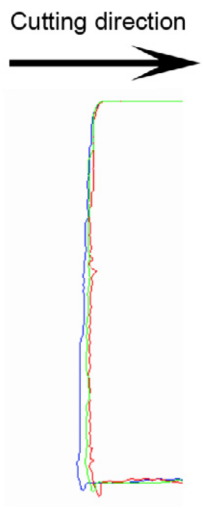


Fig. 5. Red, green and blue lines on the right side respectively represent the simulated cutting front at minimum, medium and high cutting speed for of 6-mm-thick stainless steel

4. Summary

The LIP formation in fusion laser cutting of stainless steel proved to be related to the type of the assist gas rather than the workpiece material. An increase in cutting speed results in increased inclination of the process front, which in two different ways enhances the heat transfer from the melt pool to the assist gas. More importantly, it increases the absorption coefficient of the melt layer and thus raises the melt temperature. Another consequence of an increased inclination angle of the cutting front, which may be of a marginal effect compared to the first one, is increased contact area between the assist gas and the melt pool which enhances the heat transfer from the melt pool to the assist gas.

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